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Olesen, Frits Bolonius

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FIRE ENGINEERING DESIGN OF TIMBER STRUCTURES

by

Frits Bolonius Olesen, University of Aalborg

INTRODUCTION

In Eurocode 5: Design of Timber Structures (still in preparation spring 1993) is included a Part 10: Structural Fire Design. Although this part of the code, as is the case with the Eurocode-complex in general, is primarily based on the concept of Standard fire exposure, according to ISO 834, it also gives principles for a more differentiated structural fire design based on the concept of "natural" or "parametric" fire exposure, i.e. a fire exposure including both a period of increasing temperature and a subsequent period of cooling, determined by the fire load, the ventilation properties and the thermal properties of the fire compartments as the governing parameters.

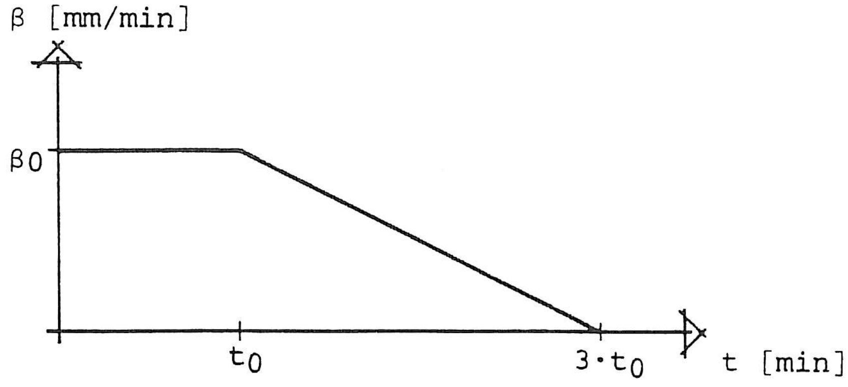
The last-mentioned concept of structural fire design, of course, demands more differentiated rules and approximations with respect to charring rates, material properties and structural response, than the simplified concept of standard fire design. Some of the background material for this are wellknown facts, but due to the lack of sufficient information, supplementary investigations have to some extent been carried out in the recent years. Some of this prenormative research has been made at The University of Aalborg, where a series of full-scale tests with parametric fire exposure on loaded glulam beams were performed in the structural fire laboratory.

CHARRING RATES IN NATURAL FIRES

Structural fire design based on the concept of "natural" or "parametric" fire exposure, which is, as mentioned above, an alternative to the concept of Standard fire exposure, has been wellknown and accepted for several years in the Scandinavian countries. In Svensk Bygg Norm (Swedish Building Code) 1975 it is prescribed that for fire compartments with an opening factor $> 0.04\ \mathrm{m}^{\frac{1}{2}}$ the increased charring rate is taken into account, and correspondingly, the Danish Code for the Structural Use of Timber DS 413 (4th ed. 1982) specifies simplified expressions for the calculation of the dependence of the cross-sectional reduction on the opening factor and the fire load density.

The background for these Danish expressions is an analysis of the charring rate for 1-dimensional thermal action carried out and published in 1981 by HADVIG [1], who set up expressions for determination of the time-variation of the charring depth dependent on the thermal action.

As a slightly simplified formulation of Hadvigs expressions for the charring depth the time-variation of the charring rate β can be expressed as follows:



$$\beta_0 = \frac{5 \cdot F - 0{,}04}{4 \cdot F + 0{,}08} \quad \text{[mm/min]} \quad [0{,}02 < \text{F} < 0{,}30\ \text{m}^{\frac{1}{2}}]$$

$$t_0 = 0{,}006 \cdot \frac{q_t}{F} \quad \text{[min]} \quad [0 < t_0 \leq \begin{cases} 40 & \text{min} \\ b/(8 \cdot \beta_0) & \text{min} \end{cases}]$$

Figure 1. Simplified relationship between charring rate and time in natural fires.

where

F	=	$A \cdot \sqrt{h}/A_t$	[$\text{m}^{\frac{1}{2}}$]
A	=	Sum of area of vertical openings	[m^2]
A_t	=	Total area of enclosing surfaces	[m^2]
h	=	Weighted mean value of opening height	[m]
b	=	Smallest cross-sectional dimension	[mm]
q_t	=	Fire load density	[MJ/m^2]

The expression applies to vertical sides of glulam beams mainly exposed to wooden fuel fires.

EXPERIMENTAL INVESTIGATIONS

The test series has included 18 full-scale fire tests performed in the combined furnace/beam testing machine of the laboratory where the test specimens were exposed to fire on 3 sides (protected on the upper side). A further description of the testing equipment is given in [2]. The test specimens were approx. 4 m long in 3 series with the cross-section $h \times b =$

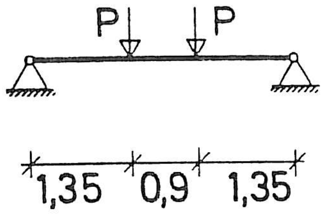
300 × 140 mm (G 05 - G 11)

300 × 160 mm (G 21 - G 26)

300 × 185 mm (G 31 - G 36)

The test specimens fullfilled the requirements of strength class L30. The flexural stiffness of each beam was determined prior to each fire test.

The initial loading on the test specimens (simply supported with a span of 3.60 m) was 2 concentrated loads P_0 of



5,0 kN (G 05 - G 11)
7,0 kN (G 21 - G 26)
8,0 kN (G 31 - G 36)

respectively, for the 3 series of beam tests, and was held constant during the major part of the fire tests.

The load level was chosen to be low in order to prevent lateral buckling, since the beams were not braced during the period of fire exposure. When the gas temperature in the furnace had decreased to about 300 to 250°C the fire was extinguished with water, bracings were attached to the test beam, and immediately after the static loading was increased until the failure load P_u of the beam was reached.

The thermal action was controlled by a gas temperature time relationship calculated by an energy balance method (the opening factor method) using the following fictitious opening factors F and fire load densities q_t:

opening factor F ($m^{\frac{1}{2}}$):	0.04	0.06	0.08		
fire load density q_t (MJ/m^2):	113	126	151	188	251

combined to a total of 6 different temperature/time relationships. In each test the fire exposure was extinguished with water at the time when the temperature of the furnace was approx. 300°C during the cooling down phase, approximately corresponding to the maximum weakening of the cross-section.

The temperatures in the test specimens were measured by drilled-in thermo elements and were recorded continuously during the tests. For technical reasons during the tests, however, these measurings were performed separately on special test specimens (G 45-98, a total of 30 test specimens) of identical geometry, moisture content etc. and exposed to the same thermal action as during the full-scale tests.

The deflections at 4 points (150 and 750 mm, respectively, from the centre point of the beams) were continuously recorded during the tests.

The charring depth was measured after the tests by means of brushing off the char, and the charring depth was measured in 4 cross-sections of each beam. In each section the depths were measured at ten gauge points at each vertical side and at five points at the bottom side of the beam. In the case of long duration of fire exposure it was practically possible to make measurements at the bottom side only at the middle three gauge points.

TEST RESULTS

The test results are reported in detail by BOLONIUS OLESEN [3] (in Danish) and by TOFT HANSEN & BOLONIUS OLESEN [4]. In BOLONIUS OLESEN & KÖNIG [5] is given a summary of the test results, and deduction of simplified strength expressions are carried out.

Typical test results are presented in figure 2, showing for test no G07 the time-dependent temperature in the furnace, and the corresponding deflection of the test beam at the two gauge points. The indices in the notations refer to the distance of the gauge point from the middle of the beam in centimetres. The figure represents one specific combination of fire load conditions.

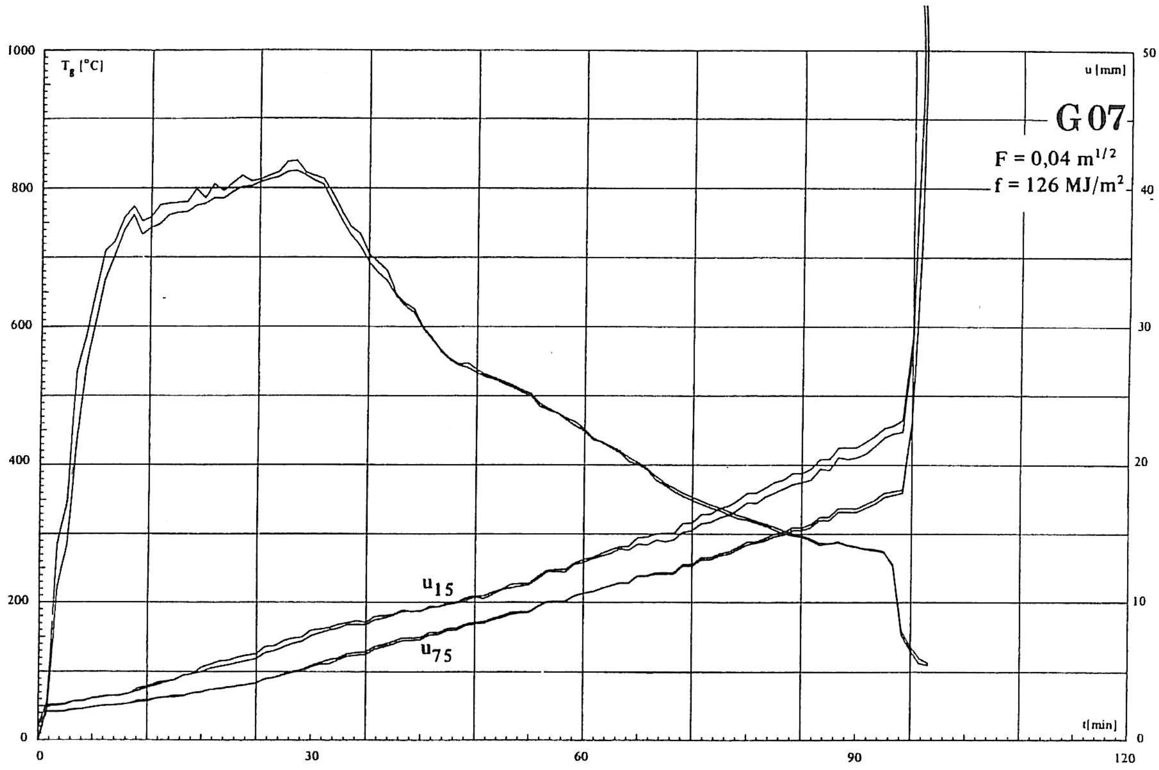


Figure 2. Example of gas temperature in the furnace and deflection of the test beam versus time.

It is obvious that the deflection of the beams increases during the whole cooling period at about the same rate as in the initial period with increasing temperature. The rate of loss of stiffness is not affected by the fact that the maximum charring depth is already reached at the time of $3t_0$ according to Equation (3), which is considerably smaller than the time at which the load was increased.

In figure 3 the results of the charring depth measurements are presented for 4 tests, all of them with an opening factor $F = 0.08m^{\frac{1}{2}}$. The measured values of the mean charring depths on the vertical beam sides with the corresponding calculated values are inserted.

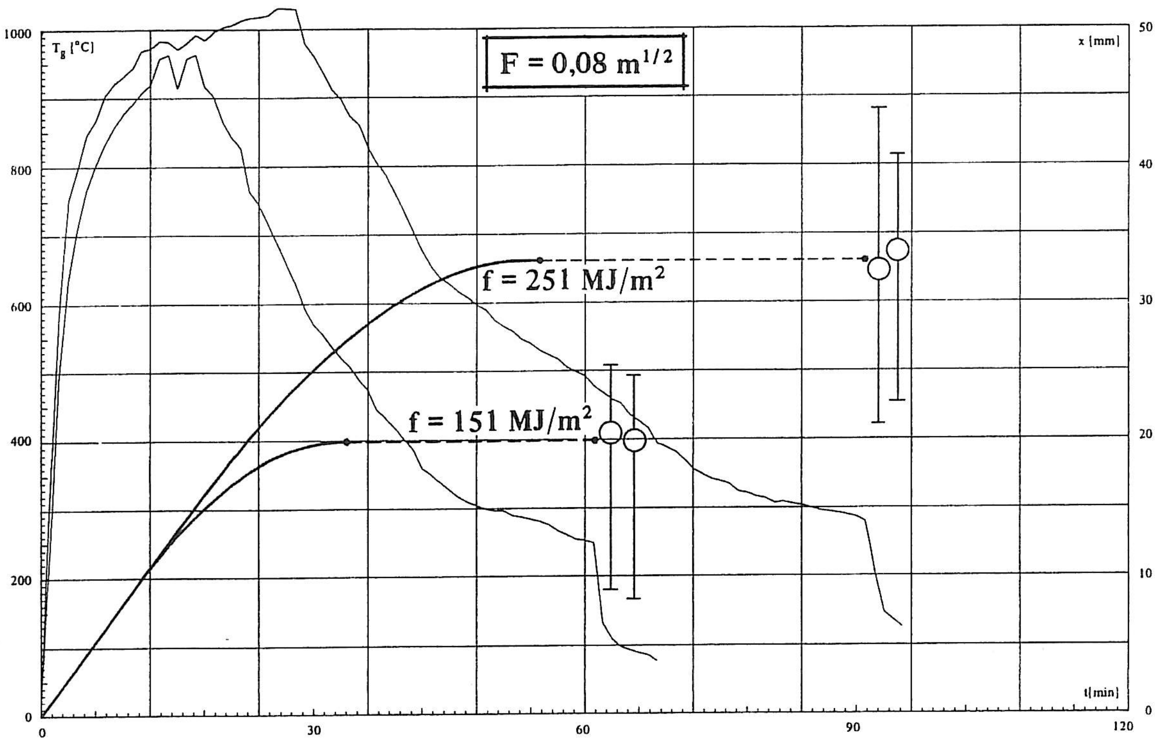


Figure 3. Measured and calculated values of the mean charring depth on the vertical beam sides of 4 test specimens.

The average charring depths are given in the table

where $d_{char,w}$ average charring depth on the wide side

$d_{char,n}$ average charring depth on the narrow side.

The agreement of measured and calculated values on the wide side according to Hadvig [1] is good.

No.	$d_{char,w}$ test	$d_{char,n}$ test	$3t_0$ calc.	$d_{char,w}$ calc.	h_r	b_r	$f_{m,r}$	f_r / 40	f_r / 30
	mm	mm	min.	mm	mm	mm	MPa	-	-
G 07	24,1	32,2	57	25,2	266	89	16,2	0,405	0,540
G08	16,4	17,7	34	18,4	278	103	22,4	0,560	0,747
G 09	20,3	22,8	34	20,4	273	95	23,6	0,590	0,787
G 23	26,0	28,3	57	25,2	270	106	17,5	0,438	0,583
G 25	32,0	36,9	56	33,9	271	94	15,5	0,388	0,517
G 26	20,0	22,3	34	20,4	276	118	27,1	0,678	0,903
G 32	38,9	40,4	85	37,6	259	106	13,2	0,330	0,440
G 33	29,4	26,4	56	30,7	272	124	17,3	0,433	0,577
G 34	34,1	30,6	56	33,9	266	115	19,7	0,493	0,657

Table. Test results (charring depths and bending strengths).

Using the depth h_r and width b_r of the residual cross section, i.e. the initial cross section minus the char layer, the bending strength $f_{m,r}$ was calculated. If we assume that the bending strength of the test beams at normal temperature was 40 MPa (the mean bending strength of Nordic glued laminated timber is about one third greater than the characteristic value), the bending strength ratio

$$k_r = \frac{f_{m,r}}{f_m} \tag{4}$$

of the residual cross section, see the table, can be presented as a function of the relative charring depth $d_{char,w}/b_0$:

$$k_r = 0,98 - 3,02\ \frac{d_{char,w}}{b_0} \tag{5}$$

For comparison this has been done also for $f_m = 30$ MPa.

This relationship shows that the amount of charring, or indirectly the duration of time, is important for the reduction of bending strength of the residual cross section. With increasing charring a greater part of the cross section is affected by elevated temperature caused by continuous heat flow during the cooling period.

STRUCTURAL FIRE DESIGN IN EUROCODE 5: DESIGN OF TIMBER STRUCTURES

The results of the tests carried out are some of the background material for Annex B in the Part 10: Structural fire Design, of the Eurocode 5 (Draft spring 1993). Thus, in this annex it is stated, that the maximum charring depth for glulam structures can be calculated as

$$d_{char} = 2 \cdot \beta_{par} \cdot t_0 \quad \text{[mm]}$$

where

$$\begin{aligned} \beta_{par} &= \tfrac{5F-0.04}{4F+0.08} \cdot 1.05 \quad \text{[mm/min]} \\ t_0 &= 0.006 \cdot \tfrac{qd}{F} \quad \text{[min]} \end{aligned}$$

The expressions and the symbols used, as well as their application limits are identical with those presented in the first page of this article.

Furthermore it is stated in the Annex B, that for glulam beams with an initial width of 130 mm or more the lowest load carrying capacity during the complete fire endurance may be calculated using the residual cross section and a design strength $f_{d,f}$ equal to the normal bending strength (with a partial coefficient $\gamma_{m,f} = 1.1$) multiplied by a modification factor

$$k_{mod,f} = 1.0 - 3.2 \cdot \frac{d_{char}}{b_n}$$

which is a slightly modificated formulation of the function deduced above.

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